Modeling Coastal Ocean Optical Properties for Coupled Circulation and Ecosystem Models

Curtis D. Mobley
Sequoia Scientific, Inc.
Westpark Technical Center
15317 NE 90th Street
Redmond, WA 98052
phone: 425-867-2464 x 109 fax: 425-867-5505 email: mobley@sequoiasci.com

Award Number: N0001497C0019
http://www.opl.ucsb.edu/hycode.html

LONG-TERM GOAL

The overall goal of this work is to develop an extremely fast but accurate radiative transfer model, called Ecolight, for use in coupled physical-biological-optical ecosystem models, and then to use those models for understanding the ocean optical environment.

OBJECTIVES

Currently available ecosystem models often use fairly sophisticated treatments of the physics (e.g., advection and near-surface thermodynamics and mixing) and biology (e.g., primary production and grazing) but use grossly oversimplified treatments of the optics. The optics component of coupled ecosystem models is sometimes just a single equation parameterizing the scalar irradiance or photosynthetically available radiation (PAR) in terms of the chlorophyll concentration. Such simple models often fail even in Case 1 waters, and they can be wrong by orders of magnitude in Case 2 waters. The objective of this year's work was to continue developing a radiative transfer model that can be used in coupled models to bring the optics component up to the level of accuracy and sophistication needed for ecosystem models that are being applied to any water body, including Case 2 waters.

APPROACH

The HYDROLIGHT radiative transfer model (http://www.sequoiasci.com; see also Mobley and Sundman, 2001a,b) provides an accurate solution of the radiative transfer equation (RTE) for any water body, given the absorption and scattering properties of the water body and boundary conditions such as incident sky radiance and bottom reflectance. Unfortunately, the standard version of Hydrolight requires too much computer time to make it suitable for use in ecosystem models where the light field must be computed at many grid points and at time intervals of less than one hour. However, ecosystem models require only the scalar irradiance as a function of depth and wavelength, $E_o(z,\lambda)$, or PAR(z), which makes it possible to optimize the Hydrolight code to run extremely fast. I therefore tailored the Hydrolight 4.1 code to run as fast as possible with the constraint that the computed PAR value at the bottom of the euphotic zone must be accurate to ten percent. The resulting highly optimized version of Hydrolight 4.1 is called Ecolight. Although it is still necessary to solve the radiative transfer equation to obtain the radiance distribution (from which the scalar irradiance is then

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**
4. TITLE AND SUBTITLE **Modeling Coastal Ocean Optical Properties for Coupled Circulation and Ecosystem Models**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Sequoia Scientific, Inc.,Westpark Technical Center,,15317 NE 90th Street,Redmond,,WA, 98052**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The overall goal of this work is to develop an extremely fast but accurate radiative transfer model, called Ecolight, for use in coupled physical-biological-optical ecosystem models, and then to use those models for understanding the ocean optical environment.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

computed), the radiance can be computed with less angular resolution, at fewer wavelengths, and to shallower depths and still obtain acceptably accurate scalar irradiances and PAR values.

WORK COMPLETED

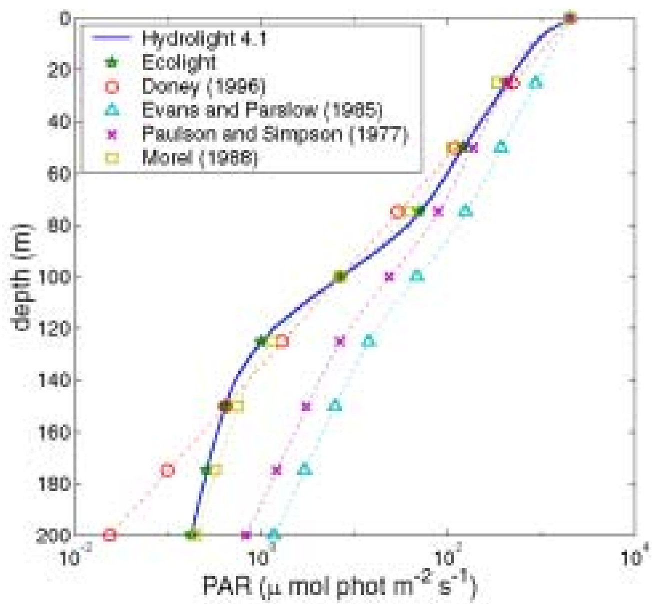
This year's work continued the development of Ecolight and examination of the spectral scalar irradiance as a function of depth and wavelength for a variety of waters, including Case 1 waters with low to high chlorophyll concentrations and Case 2 waters with high concentrations of colored dissolved organic matter (CDOM) and mineral particles. The purpose of this study was to see how various PAR models performed under different conditions and to evaluate the performance of Ecolight against Hydrolight and the currently used analytical models. This work used a stand-alone version of Ecolight. The next step, which is underway, is to make Ecolight into a callable subroutine and to incorporate that subroutine into the EcoSym (Bissett, *et al.*, 1999) coupled ecosystem model. The details of this work were described in Sundman, *et al.* (2000).

I also developed a method for using measured backscatter coefficients (as obtained, for example, from a HOBILabs HydroScat-6) and total scatter coefficients (e.g., from a WETLabs ac-9) to dynamically generate (as Hydrolight runs) scattering phase functions having the measured backscatter fraction at each depth and wavelength. The comprehensive data set obtained during the HyCODE 2000 field experiment at the LEO-15 site was used to show the importance of having the right phase function when predicting upwelling radiances. This work is described in Mobley, Sundman, and Boss, 2001.

In addition to the work explicitly described here, I authored or co-authored 4 other papers and three book chapters that contribute to the overall goals of HyCODE or to other Navy needs; see the Publications for the complete list. Three papers were presented at Ocean Optics XV.

RESULTS

We now show a few results obtained in the course of this year's work. Figure 1 (from Sundman, et al., 2000) shows PAR profiles as computed by Hydrolight 4.1, Ecolight, and four simple analytical models that have been used in ecosystem models (Doney, *et al.*, 1996; Evans and Parslow, 1985; Paulson and Simpson, 1977; and Morel, 1988). In Fig. 1, which is a simulation of oligotrophic Case 1 water, the chlorophyll profile is based on measurements taken in the spring at an Atlantic Ocean site (Zielinski, *et al.*, 1998, station ESTOC). The chlorophyll concentration varied from about 0.1 mg Chl m^{-3} near the surface, to a maximum of 0.6 mg m^{-3} near 100 m depth, and decreased to almost zero below 150 m. This chlorophyll profile was converted to inherent optical properties (IOPs) using a standard bio-optical model for Case 1 water available in Hydrolight. The models were run to a depth of 200 m. The depth of the euphotic zone (the depth where PAR decreases to 1% of its surface value) is about 90 m. One of the analytical models is in error by almost an order of magnitude at 90 m, and it over predicts the depth of the euphotic zone by 30 m. Of the analytical models, only the Morel (1988) model was able to track the PAR profile, and even then the errors were as much as 30%.

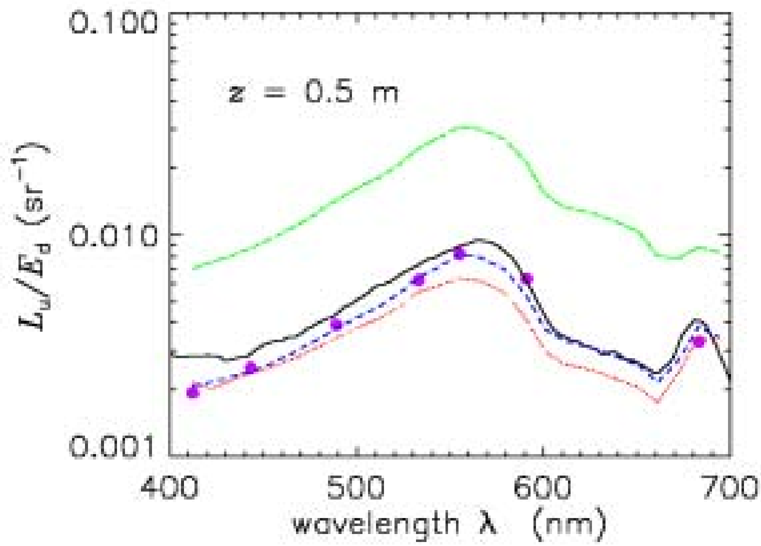


1. Simulations of PAR in oligotrophic Case 1 water. Note that Ecolight tracks the exact Hydrolight profile well, but that the analytical models can have large errors even in Case 1 water..

In these simulations, all PAR values were set to the Hydrolight value at the surface. The analytical models also can induce additional errors of ~30% due to their inaccurate estimation of the surface PAR values. Those errors then propagate with depth, in addition to the errors seen in Fig. 1.

For these simulations, Ecolight ran 1230 times faster than Hydrolight 4.1, while still providing PAR to better than 10% accuracy. Although the Ecolight times are still slower than the analytic computations, there is no justification for using the analytic models in light of their large potential errors.

Figure 2 shows measured and predicted values for the in-water remote-sensing reflectance ratio L_u/E_d. The measured values were obtained from two independent instruments (a Satlantic Hyper-TSRB and a Satlantic OCP). The predicted values were computed by Hydrolight using three different phase functions for the particle scattering: a phase function measured in situ, a dynamically determined phase function obtained from measured backscatter and total scatter coefficients, and a Petzold "average-particle" phase function. Excellent closure between measurement and prediction is obtained when using the measured phase function. The agreement is not quite as good when using the backscatter fraction to determine the phase function, but the dynamic phase functions give much better agreement with measurement than does the assumption of a Petzold phase function, which had too large a backscatter fraction for this water body.



2. Comparison of measured and Hydrolight-computed remote-sensing reflectance at 0.5 m depth. Solid black line, measured by a Satlantic Hyper-TSRB; purple dots, measured by a Satlantic OCP; dotted red line, predicted by Hydrolight with dynamically determined phase functions; dashed blue line, predicted with a measured phase function; dash-dot green line, predicted with a Petzold phase function.
[The best agreement is obtained when using a measured phase function. Phase functions dynamically determined from the measured backscatter fraction give much better results than the Petzold phase function which, in these waters, has much too much backscatter.]

In conclusion, a special version of Hydrolight 4.1, called Ecolight, has been developed for use in coupled ecosystem models. Ecolight typically runs ~1000 times faster than the standard Hydrolight code, which makes it possible to compute the spectral scalar irradiance throughout the euphotic zone in approximately one second of time on a fast personal computer. *Therefore, there is no longer any excuse for using inaccurate optical submodels in coupled physical-biological-optical ecosystem models.* It is also clearly necessary to use the correct particle scattering phase function in radiative transfer simulations. Although phase functions are rarely measured in situ, measured backscatter and total scatter coefficients can be used to generate phase functions that give much better results than just assuming a phase function, which may or may not be appropriate for a given water body.

IMPACT/APPLICATION

Predictive ecosystem models are playing an increasingly important role in our understanding of the oceans. Applications of such models range from predictions of water clarity for military purposes to management of coastal waters for fisheries. The incorporation of the Ecolight model developed here into coupled ecosystem models will give improved accuracy in the predictions of primary production and related quantities made by such models. As the coupled models become more trustworthy in their predictions, they will become even more valuable as tools for ocean science.

TRANSITIONS

Beta-test versions of the Ecolight code have been delivered to Drs. Paul Bissett and Ray Smith, who are using the code in coupled ecosystem models for the Florida shelf and the Santa Barbara Channel, respectively. Their work is also part of the HyCODE program. The algorithm for dynamic determination of phase functions has been incorporated into Hydrolight version 4.1 and distributed to all Hydrolight users.

RELATED PROJECTS

We are now starting to couple Ecolight with the EcoSym model (Bissett, *et al.*, 1999), which is being run for the West Florida Shelf HyCODE site. We expect that this collaboration will continue to be the focus of next year's work. The LEO-15 data used in the phase function closure study were provided by Drs. Scott Pegau of Oregon State University and M. Lee, M. Shibonov, and G. Korotaev of the Marine Hydrophysical Institute of Sebastopol, Ukraine, all of whom are funded separately for their HyCODE work.

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